Comparison of 3 household food waste dryers in the context of food waste prevention and bioeconomy

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Abstract

The results of the laboratory testing of 3 household waste dryers and the theoretical implementation of a state of the art biological waste drying to biomass management scheme in a major Greek Municipality, are presented within the context of this research. The novelty of this work lays on the fact that no similar study describing the actual economic benefits of households waste drying exists. The research revealed that the highest mass and volume reductions were reached with the use of the Smart Cara CS10, 78% w/w and 82% respectively while the most efficient energy consumption also recorded was 1.1 kWh/kg. The final dry product for all cases was measured to have a high starch and cellulose/hemicellulose content ($\approx 43\%$ w/w and $\approx 11.5\%$ w/w respectively) which makes it an ideal substrate for the production of biologically based materials. The initial investigation on the implementation of the biological waste to biomass management scheme using all 3 systems tested, in a major Greek Municipality, revealed there could be significant savings of 636,786,6 euros/y by using the dryer with the best performance, which could benefit the Municipality and its civilians in the short and long term. The significance of this work lays in the fact that through the use of the results of this study, Municipalities may organize and implement a waste to dehydrated biomass waste management scheme for the proper management and treatment of biowaste since actually this is the first study on the cost of the implementation of such a scheme.

Keywords Biological · Drying · Bioeconomy · Biomass · Waste

1 Introduction

The most widely used fossil fuels (oil, gas, coal), are expected to be significantly reduced or depleted within the coming 90 years based on [17], while other scientists [10] estimate that their depletion is expected to come sooner. The fact is that there are still undiscovered sources of fossil fuels such as the Arctic [8] and the Balkan region, the technology evolves, while the global demand for the coming decades cannot be quantified. These non-exhaustive factors, are expected to change these predictions thus, affecting current planning.

Fossil fuels, play a significant role, not only in the production of energy but also in the production of biobased

materials such as: chemical blocks, secondary materials and tertiary materials such as paints, textiles, cement, etc. [21].

They also affect climate change since they contribute to the CO₂ levels raise which is the 2nd most abundant Greenhouse Gas (GHG) after water vapors, and which levels have been significantly affected upwards since 1950 [12].

There is still high dependence on fossil fuels (81% in 2014 according to [11]) while there is a significant variation in their use (in terms of quantity) between countries worldwide which face different challenges (economic crisis, climate change impacts, etc.). It is noted that fossil fuels are considered to be a non-renewable source of

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energy at human level since they need millions of years to be formed.

1.3 billion tonnes of food waste is produced per year. Almost 2/3 of the total amount of MSW is comprised of food waste and paper/cardboard waste [22].

In the EU, an estimated 20% of the total food produced is lost or wasted, while 55 million people cannot afford a quality meal every second day. Households generate more than half of the total food waste in the EU (47 million tonnes) with 70% of food waste arising at household, food service and retail [6].

In the EU, 118–138 million tonnes of bio-waste (food waste is the largest fraction—88 million tonnes—out of it) is produced annually, out of which almost 25% is turned into compost [3, 4].

The rest of it is either incinerated, treated anaerobically [13] (small percentage) or landfilled.

Based on the EU 2018 Circular Economy Package, among others, bio-waste will have to be collected separately by 2023, while the separate collection rules will boost the quality of all secondary raw materials and their uptake. The 2018 update of the Bioeconomy Strategy, also gives significant attention to the use of biomass (other than agricultural) for the production of biobased products and materials [4] providing a concrete link between food security and future sustainability.

Finally, food waste prevention, is also a major Sustainable Development Goal (SDG)—12.3 (By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses).

According to [4], a major problem related to food waste as part of the larger fraction of bio-waste is the fact that it contains high water and microbial content which, taken into account the ambient temperature effect, results to its rapid decomposition, if not treated properly at source. This results to the loss of nutrients and the production of GHGs in all part of the chain (source-treatment-landfill).

Household food waste drying is a method which was first introduced by Sotiropoulos et al. [15] and provides a concrete and direct mean of waste biomass minimization, stabilization and preservation in order to be able to be used in the bioeconomy and circular economy context.

It not only contributes to the effective separation of food waste at source (99.9% purity levels based on [15]) but also to its safe collection, transport and treatment at any level. The most important is that through household food waste drying, the mass and volume of the waste material is significantly reduced.

The scope of this research is the examination and comparison of the efficiency of 3 different (2 commercialized and 1 laboratory scale) household waste dryers in order to discuss their future use not only in the context of bioeconomy but also in the context of food waste prevention and biomass production. It is stressed that the household waste drying technology covers many socioeconomic and environmental sectors horizontally thus contributing to the implementation of a large number of EU and world-wide targets.

2 Materials and methods

2.1 Methodology applied

For the purposes of the research, 3 household waste drying systems were tested: the Smart Cara CS10, the LOOFEN (commercialized systems) and the DRYWASTE household waste dryer which was developed and operated by [15] during the implementation of the DRYWASTE LIFE project. All 3 systems, operated at a laboratory scale for a period of 12 months at the National technical University of Athens. In order to implement the research, a fixed mix of food waste was used based on [20]. Some of the main technical features of these systems are recorded in Table 1.

In Fig. 1, an optical view of all 3 systems can be seen.

Each drying system operated for at least 20 full cycles, with different amounts of food waste (in terms of mass) that corresponded to the quantities produced by a one-, two- and three-member family respectively in Papagos-Cholargos Municipality in Greece. The food waste amount for a 1 member family was considered to be 410 g, for a 2 member 821 g and for a 3 member 1230 g based on [20]. Table 2 presents the percentage proportion (%w/w) of food waste material contained in the total quantity of each sample used.

Table 1 Main technical features of waste dryers

Name of household waste drying system	Weight (Kg)	Capacity (L)	Operating Temperature (°C)	Energy Consumption (kWh)	Deodorization System	Pulverization Operation
Smart Cara CS10	9	5	100	0.25/h	Activated Carbon Filter	Yes
Loofen LF07	7.4	5	60	0.7/h	Activated Carbon Filter	No
DRYWASTE	18	15	95	0.5/h	Activated Carbon Filter	No

Fig. 1 Optical view of the Smart Cara CS10 system (top), the DRY-WASTE system (bottom left), the Loofen LF07 system (bottom right)

Table 2 Percentage proportion of each food waste material used

Specimen	Food waste material	Percentage (%w/w)
1	Potato	30.24
2	Onion	5.37
3	Lettuce	2.93
4	Pepper	0.73
5	Rest of Green Salad	2.44
6	Cabbage	3.41
7	Tomato	2.44
8	Orange	4.88
9	Banana	11.46
10	Apple	9.51
11	Lemon	1.71
12	Pasta	6.59
13	Rice	6.83
14	Bread	3.17
15	Chicken	2.44
16	Pork	3.17
17	Fish	0.98
19	Cheese	1.70
Total		100

All samples were evenly cut in terms of length and thickness, the initial mass and volume were measured before the initiation of the drying process while the mass measurement took place every 10 min for the first 2 h and

every 1 h until the end of each 8 h operation cycle. The reason for that sort sampling period was that the mass reduction is in general significant during the first 2 h of the dehydration process. The final volume was calculated at the end of each daily cycle. The dehydrated material remained inside the waste dryers at the end of the daily cycle and the next day, the same procedure was repeated until all waste dryers became filled with dehydrated biomass, simulating the kitchen environment (removing waste as soon as our waste bins are filled and not on a daily basis).

The systems mass balances were analyzed and are presented on an input–output basis, measuring the total input as it enters the dryer and the final solid residue after the dehydration/drying process. The removal of water has been calculated by taking into account the balancing of masses and by measuring the moisture/water content before and after the dehydration process. By taking into account the percentage of removed water and the total input water, the dehydration efficiency was calculated. The energy demand of the drying units have been assessed on a per hour and per kg basis. The energy demand (per kg) is being compared with the ideal energy demand for water evaporation, i.e. latent heat of vaporization, in order to assess the energy efficiency of dehydration. By taking into account these two aspects, we introduced a new “total efficiency” parameter, which combines the dehydration efficiency and the energy efficiency by multiplying them. At the end of each experimental cycle, the dehydrated specimens were further pulverized to a diameter of under 1 mm in order to be further measured in terms of their chemical properties.

2.2 Methods of analysis for the evaluation of the systems performance

The following physical and chemical parameters were measured and/or calculated in order to assess the performance of the dryers and the quality of the dehydrated material:

1. The mass of the raw substrate material before, during and after the dehydration process, was measured using a laboratory digital scale;
2. The volume of the raw material substrate before, during and after the dehydration process was measured by measuring the volume of the material at every step into the waste drying baskets which shape, size and thus volume was known;
3. The energy consumption of the waste dryers was continuously measured directly with the use of an energy meter placed between the plug and the power source;

- The remaining water content of the collected biomass was determined after drying the collected samples at 105 °C for 24 h;
- The pH was measured according to EPA Method 9045D using a pH meter (Mettler Toledo MPC 227 pH/Conductivity Meter);
- The Total Organic Carbon (TOC) was measured using TOC analyzer TOC-VCSH of Shimadzu coupled with solid sample module-5000A;
- The Total Nitrogen (TN) was determined through digestion (Gerhard Kjeldaltherm KB/KBL), distillation (Gerhard Vapodest Distillation), and titration as described in the German Standard Methods for the examination of water, sewage, and sludge [1]
- The determination of structural carbohydrates was performed based on [14, 16];
- The determination of the total reduced sugars, glucose content and ethanol was performed using the method described by [2].

2.3 Initial cost–benefit analysis of the bio-waste drying scheme in a major Greek Municipality

The case study area was the Municipality of Nea-Smirni in the Attica Region, Greece. The Municipality's population is 73,076 permanent residents [9]. Based on the same source, there are 31,847 households with an average of 2.27 members/household. The total MSW quantity produced is estimated to be approximately 26.976 t/year. The existing MSW management system in place involves the source separation of packaging waste using blue bins of 1100 L. The rest of the waste is collected on a daily basis and landfilled in the landfill of Ano Liosia in the Attica region.

Since there is no source separation of household bio-waste, the quantity may only be estimated based on data from the Greek National Waste Management Plan [7]. According to the plan, the organic fraction of MSW accounts for a 44, 3% w/w of the total quantity of MSW which for our case is approximately 11,950 t/year. Based on the same plan, 86% of this quantity comes from households (10,277 t/year). The transport cost for the Municipality's bio-waste is 110 euros/t while the landfill tax is 100 euros/t. The authors considered all 3 systems for the theoretical implementation and a capital cost of 210 euros/unit, 100 euros/unit and 150 euros/unit for the Smart Cara CS10, the Loofen LF07 and the DRYWASTE systems respectively. A lifetime of 10 years and a service cost of 20 euros/year has been considered for all the devices. The volume reduction of each system was taken into consideration for the assessment of the waste volume reduction. Since the biomass has already been dehydrated is has been considered after official offers received from 4 major Greek pellet industries a price for the dehydrated biomass of 30 euros/t.

It is stressed that this price was based, taken into account that the average EU price of the wood pellets of approximately 250 euros/t [5]. The agropellets have a market share of approximately 11% from the total amount of the pellets produced in the EU, while there is no data for pellets produced from bio-waste.

3 Results and discussion

3.1 Waste dryers' performance comparison

The %w/w mass reduction of household bio-waste for all waste dryers is recorded in Fig. 2.

The Smart Cara CS10 drying system was recorded to have the highest mass reduction for all waste quantities tested (average mass reduction of approximately 78% w/w) while the Loofen LF07 and the DRYWASTE systems had an average mass reduction of approximately 70% and 72% w/w respectively. The average volume reduction for the Smart Cara CS10, the Loofen LF07 and the DRYWASTE were found to be approximately 82% w/w, 58% and 59% w/w respectively. Figure 3 presents the mass balances for the three drying systems and shows the separation of streams. The values are consistent with the values that are reported from other published studies [14, 18]. In each case, a percentage of water is removed and this should be accounted along with the energy utilization of the system.

The average energy consumption was found to be 1.1 kWh/kg, 1.8 kWh/kg and 2.8 kWh/kg for the Smart Cara CS10, the Loofen LF07 and the DRYWASTE systems respectively. The results reveal that all three systems may achieve the targets set by the landfill directive for bio-waste mass minimisation with the Smart Cara CS10 being the most efficient in terms of mass and volume reduction.

Figure 4 shows the efficiencies of each system as described in the section materials and methods.

All three systems revealed high dehydration efficiencies, which ranged from 90% to 98%. Nonetheless, the critical

Fig. 2 %w/w mass reduction of household bio-waste for all waste dryers

Fig. 3 The mass balances for the three drying systems

parameter is the energy utilization which is vastly different for each with the Smart Cara CS10 having 57%, the Loofen LF07 34.8% and the DRYWASTE 22.4%. The combination of the dehydration efficiency and the energy efficiency provided the total efficiency of each dryer with the Smart

Cara CS10 having 55.6%, the Loofen LF07 31.2% and the DRYWASTE 20.9%. A critical comment on the efficiency of these dryers is that smaller systems seem to have less energy-intensive operations and this could be attributed to the small compact designs that minimize heat losses. Vakalis et al. [19], have reported the operation of a bigger and centralized dehydration system, which has shown that design optimization, is very effective in reducing the energy demand even in systems with bigger capacities (Table 3).

Table 3 presents the results of the physicochemical analyses of the final dehydrated material for all waste dryers and all cycles.

The physicochemical analyses of the final dehydrated material, showed that the Smart Cara CS10 waste drying system, produced a material with almost 2% w/w water content making it the most effective from all 3 waste drying systems. The rest of the parameters don't seem to be affected by the drying process. What should be stressed out is the fact that the final dry product has high starch, cellulose and hemi-cellulose content (almost 50%w/w for all cases) which makes it ideal for the production of a series of biobased products as recorded by [21] but also pellets.

Fig. 4 Efficiencies of all three systems

Table 3 Results of the physicochemical analyses of the final dehydrated material for all waste dryers and all cycles

Parameter	Smart Cara CS10	Loofen LF07	DRYWASTE
Water content (%w/w)	1.91 ± 0.12	8.27 ± 0.45	5.28 ± 0.34
VS (%w/w)	85.30 ± 2.28	90.32 ± 2.32	95.01 ± 3.21
pH	4.71 ± 0.83	5.58 ± 1.21	4.96 ± 0.72
TOC (%w/w)	54.90 ± 2.44	47.58 ± 2.98	53.16 ± 2.28
TN (%w/w)	1.37 ± 0.08	2.58 ± 2.12	1.23 ± 0.03
TKN (%w/w)	0.82 ± 0.01	2.52 ± 0.64	1.16 ± 0.02
NH ₄ -N (%w/w)	0.14 ± 0.02	3.07 ± 0.33	0.07 ± 0.01
N-NO ₃ (%w/w)	0.55 ± 0.012	0.06 ± 0.01	0.07 ± 0.02
Water soluble materials (%w/w)	26.79 ± 4.48	22.45 ± 2.84	23.24 ± 2.56
Starch (%w/w)	42.96 ± 2.81	39.31 ± 2.56	38.18 ± 4.22
Cellulose-Hemicellulose (%w/w)	11.52 ± 2.55	10.53 ± 2.55	14.89 ± 1.53

3.2 Implementation of the waste drying method in a major Greek municipality

The results of the theoretical implementation of the bio-waste to biomass waste management scheme using all 3 systems are recorded in Table 4.

Based on the theoretical simplified form of the Cost–Benefit analysis conducted, a significant benefit of a maximum of 6,367,866 euros for a 10 years operation may be achieved if the bio-waste to biomass waste management scheme is implemented in the Municipality of Nea Smirni, at large scale using the Smart Cara CS10 waste drying system. This translates to a 636,786.6 euros/y of initial savings which may be used for the benefit of the Municipality and the civilians. In regard to the Loofen waste dryer, the savings were calculated equal to 5,349,157 euros (534,915.7 euros/y) and the DRYWASTE waste dryer achieved 4,250,102 euros (425,010.2 euros/y). All 3 waste dryers have revealed potential savings for the Municipality. It is stressed that a sensitivity analysis regarding the capital costs and the performance of the source separation scheme was not conducted since, the cost of the dryers was based on an official price taken by the commercial providers while, a 99,9% purity of the waste drying method has been recorded by [15]. The price of 30 euros/t of the dry material is also considered to be rather low (worst case scenario) for our calculations. The fact that there will be a production of pure dehydrated and pre-treated biomass is also expected to contribute to the Municipality's path towards circular economy. More research on additional savings from the exploitation of the dehydrated biomass should be considered at a next stage.

3.3 Practical implications of the study

The results of this work are considered to be quite important since this is the first time 3 different household waste drying systems were tested in terms of their overall performance and also evaluated in terms of their economic feasibility having real technoeconomic data. The proposed biowaste management scheme could be one of the solutions for Municipalities all over the world that are in need of finding a concrete way for handling the biowaste stream promoting bioeconomy through the production of mixed, stabilised biomass which could be further used for the production of biobased products.

The main challenge of this work is the energy needed for the dehydration process which should be the effort of future works in this field. The use of renewable energy resources may be the solution to this challenge (environmentally and economically).

4 Conclusions

Out of the 3 household waste drying systems tested at a laboratory scale, the Smart Cara CS10, provided the highest results regarding mass and volume reduction (78% w/w and 82% respectively), the DRYWASTE waste dryer provided 70% w/w and 58% mass and volume reductions respectively and the Loofen LF07 waste dryer provided 70% w/w and 58% mass and volume reductions. The energy consumption for all 3 systems was 1.1, 2.8 and 1.8 kWh/kg respectively. The final dehydrated material in all cases, may be used for the production of a variety of biobased materials due to its carbohydrate content.

The combination of the dehydration and energy efficiencies provided the total efficiency of each dryer with

Table 4 Theoretical implementation of the bio-waste to biomass waste management scheme basic economics

a/a	Smart Cara CS10	Loofen LF07	DRYWASTE
<i>Waste management scheme organization cost</i>			
Capital cost for a 10 years period considering a for 31,847 households	6,687,870	3,184,700	4,777,050
Operational cost for 10 years (dryers service cost)	6,369,400	6,369,400	6,369,400
Public sensitization campaign/training cost	800,000	800,000	800,000
Total cost	13,857,270	10,354,100	11,946,450
<i>Savings for a 10 year period</i>			
Transport and landfill tax considering each dryer's max volume reduction and a constant waste production	19,546,854	15,024,975	15,518,270
Dry biomass sale considering a price of 30 euros/t	678,282	678,282	678,282
Total benefits	20,225,136	15,703,257	16,196,552
Total savings*	6,367,866	5,349,157	4,250,102

*It is noted that the waste dryer energy consumption has not been taken into account since it's cost is transferred to the civilians based on the pay as you throw concept, while the benefits from the fact that there will be a significantly improved recyclability of the rest of the materials due to the exclusion of the organic fraction of household bio-waste have also not been taken into co

the Smart Cara CS10 having 55.6%, the Loofen LF07 31.2% and the DRYWASTE 20.9%. The implementation of the waste to biomass waste management scheme which was theoretically implemented for the case of a major Greek Municipality considering all 3 waste drying systems, revealed that there could be a maximum of 636,786.6 euros/y savings with the use of the Smart Cara CS10 waste dryer while all 3 systems revealed significant economic benefits for the Municipality.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

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